*Sim*ulated *P*roductivity *L*ost by *E*rosion (*SimPLE*): Model development, validation and use.

K.J. Greer*, J.J. Schoenau, D.W. Anderson, and C.R. Hilliard.
University of Saskatchewan, Saskatoon, Saskatchewan.

ABSTRACT

Productivity lost due to soil erosion can be estimated by existing computer simulation models such as EPIC, NTRM and CENTURY. However, these models require extensive input data and, to date, have had limited success in simulating Western Canadian conditions. The objective of this study was to develop a simple spring wheat model which captured the essential relationships between topsoil erosion and productivity loss in Chernozemic soils. Key relationships in our model describe: (i) how plants create yield from water, N, and P; (ii) how the soil provides these nutrients, and (iii) how erosion impacts on the supply of each nutrient. These relationships were logically connected using the Stella® II modeling environment. Agreement was highly significant ($r = 0.55^{***}$) between predicted and observed grain yields over 75 site years at Indian Head, Saskatchewan. Also, grain yields from scalped Chernozemic soils in Alberta were closely simulated ($r = 0.86^{****}$) by ***SimPLE***. Fifty representative soil profiles from the Brown, Dark Brown and Black soil zones were eroded in ***SimPLE*** to numerically describe the production lost under wet, normal, and dry scenarios, with and without optimum fertilizer. Yield loss, as a percentage of non-eroded yield, increased with increasing soil erosion following a trend very similar to that reported in field studies. ***SimPLE*** is flexible and can be used for analysis of "what if" management scenarios or calculating soil loss tolerance (T) values.

INTRODUCTION

Erosion is a process which selectively removes the organic matter-rich topsoil. Soil organic matter decline is detrimental to many soil parameters which, to varying degrees, impact on crop yield. An obvious intuitive relationship springs to mind where more erosion leads to less topsoil, less SOM, and less grain yield. Depth of topsoil and scalping studies, for the most part, concur with this mental model (Cowell and de Jong, 1993; Larney, 1992). However, some notable exceptions exist.

Tanaka and Aase (1989) found that on the two dry years in their five year study, scalping did not decrease yield. This suggests that moisture limitation can overshadow the loss of SOM and soil fertility. Contrary conclusions are given by Havlin et al.(1991). They report that "Below average annual rainfall increased the negative effects of soil erosion... as we would expect." Havlin's conclusions suggest that the main impact of erosion is to limit the soils ability to supply moisture. Clearly, generalized curves relating average yield and soil depth do not explain the interactions between erosion, topsoil loss, and the supply of plant requirements on every soil type, moisture condition and management.

Interactive computer models, such as **CENTURY**, or the Erosion/ Productivity Impact Calculator (**EPIC**), logically combine knowledge of the soils ability to supply certain plant requirements, with selected weather and management conditions (Williams et al 1982; Cole et al, 1989). Such models, although robust, are often very complicated and poorly validated, especially under western Canadian conditions (Cassel and Fryrear, 1990; Greer et al., 1991; Beckie and Moulin, 1992).

We felt that the productivity lost by erosion, on the Chernozemic soils in western Canada, could be better described by modelling those soil processes and properties affected by erosion and essential to wheat production. This paper will briefly describe how a ***Sim****ulator of* ***P****roductivity* ***L****ost by* ***E****rosion* (***SimPLE***) was created, current validation against observed data, and current and potential uses for this tool.

MODEL DEVELOPEMENT AND DESCRIPTION

We began modelling from the premise that crop yields on Chernozemic soils in Saskatchewan are most often limited by available water, available N and available P, and that erosion affects the ability of the soil to supply these factors. The task of logically connecting erosion to each soil property or process and each soil property or process, in turn, to crop yield was attempted using the STELLA® II temporal modelling environment .

STELLA® II is a numerical integration program which uses flow chart-like diagrams to track the changes in connected variables over time. Describing the logic between variables is far less complicated than programming in standard computer languages since creating a 'Flow' diagram is very similar to conceptual models of the soil system (eg. Anderson, 1991; van Veen and Paul, 1981). Formulating and testing logic using this software requires little programming experience. Further detail on attributes and applications of STELLA® II can be obtained from demo disks or software documentation available through High Performance Systems Inc., 45 Lyme Road, Suite 300 Hanover, NH 03755 USA, phone: 603-643-9636.

A detailed diagram of the ***SimPLE*** STELLA® II model is shown in Figure 1. This model has five main components: 1). soil organic matter (SOMC) - N supply; 2). Soil P supply; 3). Soil water supply; 4). Erosion , and 5). the initialization pod.

At the end of each one year time-step, grain and residue is produced based on the combined sufficiencies of water, N, and P which are made available from the soil. Currently only continuous wheat cropping with any level of fertilizer N and P or soil erosion can be simulated.

Soil organic matter Carbon - Nitrogen supply

SOMC is the heart of a Chernozemic soils fertility. Farmers on Chernozemic soils know that, next to water, added nitrogen will give the largest yield response. Supply of soil N is controlled by the amount and type of the SOMC. As the amount or the type of SOMC changes the soil's quality to supply N and produce grain. ***SimPLE*** also moderates N turnover depending on moisture and temperature conditions (Hinman, 1974; Ellert, 1991)

SOMC is formed from the residue generated by grain production. Residues are partitioned between SOMC, Surface Trash and CO_2 at 30, 30, and 40% per year, respectively (Stroo et al. 1989).

Soil erosion works to reduce SOMC quantity and quality, thereby limiting N supplying power. Erosion removes the surface layer which is most concentrated in SOMC and causes a concomitant reduction in turnover (Greer et al., 1992a). Lower N turnover has been linked to chemical and physical protection of SOMC with depth (Hadas et al., 1986; Roberts, 1985).

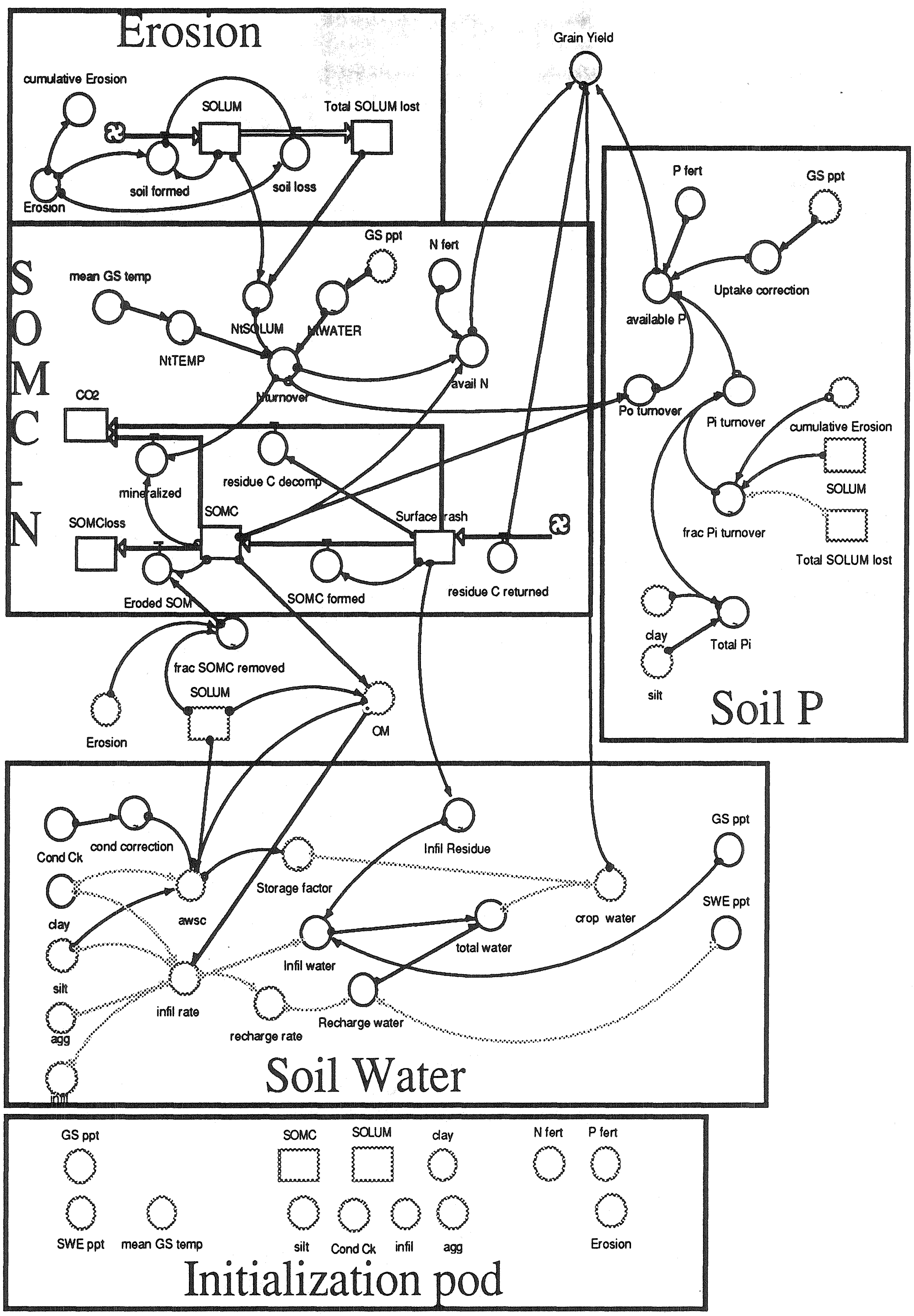


Figure 1. Detailed Stella® II Diagram of the *SimPLE* model.

Phosphorus supply:

Soil P is made available in ***SimPLE*** from inorganic (mineral), organic and fertilizer sources. Turnover of inorganic P is reduced slowly as erosion removes the leached A horizon and tillage mixes carbonates into the surface (Smith, 1948). Once the entire solum is lost, the low solubility of subsurface P minerals greatly restricts P availability.

Organic P is supplied as a function of SOMC turnover assuming a C:N:P mineralization ratio of 100:10:1. Field experiments under different levels of growing season precipitation indicate a reasonably constant 10 to 1 ratio of N and P accumulation in plants; suggesting concomitant N and P supply from organic matter.

Only 25% of the fertilizer P is considered to be available for plant growth. ***SimPLE*** may overestimate the limitation of P in fertilized, highly eroded scenarios since the unavailable fertilizer portion is not added to the total inorganic (mineral) P.

Soil Water supply

Water available for crop growth in dryland agriculture is the sum of the total rainfall from May to July (*GS ppt*) and precipitation accumulated since the last crop (*SWE ppt*). ***SimPLE*** focuses on the soil properties which, when summed over a growing season, control the infiltration and storage of precipitation. Annual infiltration rate (*Infil rate*) is calculated using the K (runoff) factor from the USLE (Wischmeier and Smith, 1978). ***SimPLE*** assumes that 1-K (1-runoff) is the proportion of water which enters the soil. Such an assumption appears realistic since a soil with high runoff and water erodibility (K approaching 1) should have a very low net infiltration (1-K approaching 0). Entry of growing season precipitation is also controlled by surface trash cover (Mannering and Meyer, 1963). Precipitation outside of the growing season enters the soil (via. recharge rate) at one half of the infil rate. Overviews of field research into overwinter recharge of stubble plots indicates nearly half of the equivalent snow water that falls is infiltrated and present in the spring (Patterson, 1985; Innovative Acres Report, 1988). We assume that the lighter soils which maintain high infil rates also have higher recharge rates.

The storage factor regulates the annual amount of crop water available for grain production according to a sufficiency function developed after Kiniry et al. (1983). Simply put, the proportion of the total water stored in the soil and available for crop use, increases as the available water storage capacity (*awsc*) increases. Estimates of *awsc* are based on the regression equations developed for Saskatchewan soils (de Jong, 1967).

Erosion of the surface soil moves the water extraction zone down into the parent material, which may contain significant salinity. Conductivity in the Ck (*cond Ck*) is used to restrict the available water due to osmotic suction. Similar logic is used in the SaskCROP model (de Jong et al., 1988).

Erosion of Topsoil

SimPLE requires erosion level (≥ 0 t ha^{-1} yr^{-1}) as an initializing input. Soil erosion simply strips away some depth of solum per time step. Loss of depth is accompanied by a loss of SOMC and reduced N and P supply. Water holding capacities generally tend to increase with erosion assuming texture is relatively constant (Morrison-Ives,1992: Kenyon, 1987). However, as erosion limits fertility and grain yield, lower levels of surface trash decrease water infiltration and available crop water.

Initialization Variables

Thirteen initialization parameters are need to run ***SimPLE***. They are grouped in Fig. 1 (the Document window) in order of importance and sensitivity from left to right. It is essential that initialization variables are input as listed in Appendix A.

Meteorological information is required for the *GS ppt*, *SWE ppt* and *mean GS temp*. Reference sources for these parameters exist as maps (Elliott and Pennock, 1990) or as tables (Treidl, 1978).

Initial soil variables, such as the amount of *SOMC*, depth of *SOLUM*, *clay* and *silt* content, and conductivity of the Ck (*Cond Ck*), have increasing influence on grain yield, respectively. Saskatchewan Soil Survey (1990) Layer file is a useful source of this information. Other less important initial variables are *Infil* and *agg* (Rostad and Hilliard, 1990).

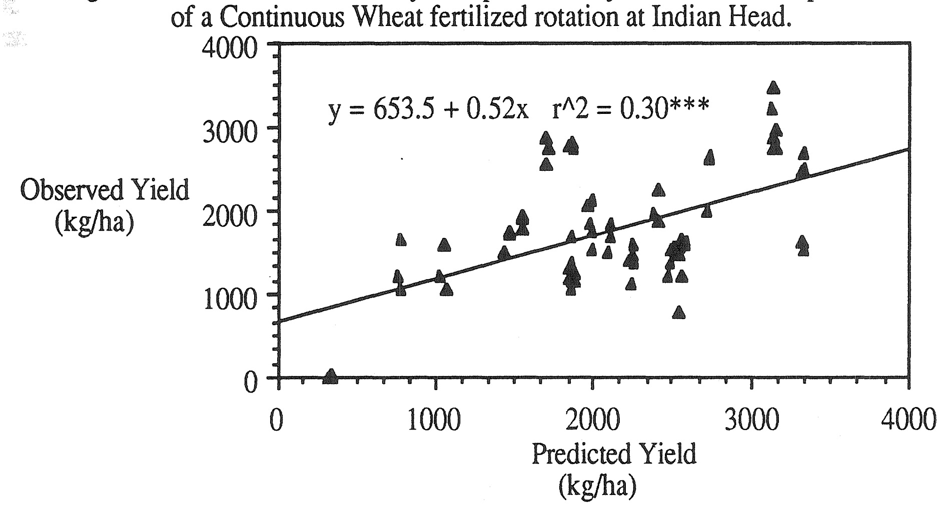
Erosion rate will vary with management and possibly soil zone. Estimates from CanHelp could be used for initialization (PFRA, 1992). Measured estimates of net soil removal on a landscape scale are given by Pennock and de Jong (1990).

NUMERICAL VALIDATION OF *SimPLE*

Testing the accuracy of SimPLE requires a data set which has all initialization parameters quantified and the key response variable (grain yield) measured. Such a data set is available for three fertilized continuous wheat plots on the Experimental Farm at Indian Head, Saskatchewan. Initial soil parameters, weather, fertilizer additions, mean erosion rates and grain yields are reported elsewhere (Greer et al., 1991; Zentner et al., 1984; Greer, 1989).

Figure 2 indicates the degree of fit between observed grain yields and those predicted by the ***SimPLE*** model for each of the 75 site•years. Regression analysis reveals a slope of 0.52 which is significantly different than 0 at the 0.01 % level.

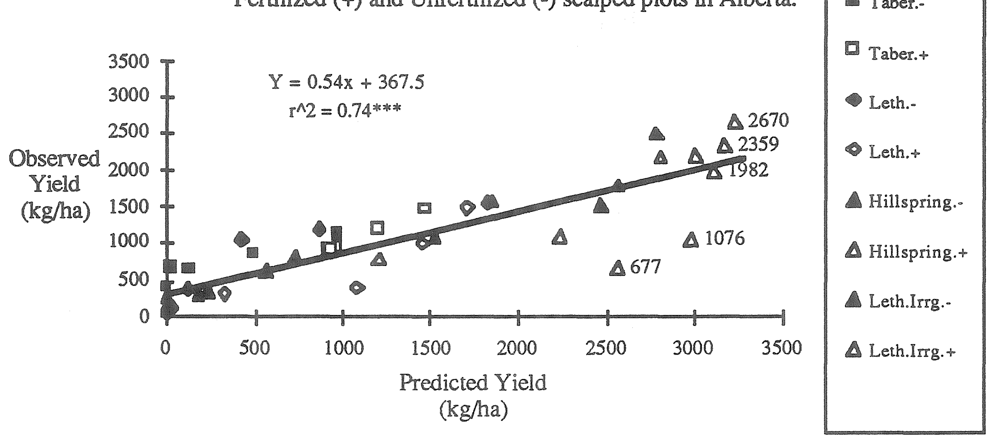
Figure 2. Validation of Wheat yields predicted by 'SimPLE' for Reps 2, 3, and 4 of a Continuous Wheat fertilized rotation at Indian Head.



SimPLE predicted yields explain 30% of the variability in observed yields. This is significantly ($P \leq 0.08$) more variability than that explained by the strongest input variable, precipitation (r^2=0.12***). Hence, the added knowledge of the soil, management, and erosion, interacting in **SimPLE**, is improving the prediction of grain yield.

Scalping studies, simulated by ***SimPLE***, give further validation of grain yields on severely eroded soils. Predicted grain yields are very closely related to observed grain yields at four study sites in the Brown, Dark Brown and Black soil zones in Alberta (Larney,1992). ***SimPLE*** explains greater than 72% of the variability in observed yields on the eight combinations of soil type, fertilizer and precipitation or irrigation (Figure 3). Lack of fit in the Irrigated with high N and P fertilizer suggests that some nutrient other than water, N and P was limiting grain yield on this site. Despite the poor prediction of the Irrigated-fertilized treatment, ***SimPLE*** can predict grain yields as well as a much more complicated and detailed erosion-productivity model (Izaurralde et al., 1992).

Figure 3. Validation of Spring Wheat yields predicted by 'Sim.P.L.E.' for Fertilized (+) and Unfertilized (-) scalped plots in Alberta.



CURRENT USES OF *SimPLE*

Erosion-Yield loss curves

SimPLE was developed to simulate the impact of increasing erosion on grain yields in the Brown, Dark Brown and Black soil zones. Fifty combinations of soil association and series were simulated under Wet, Normal and Dry conditions, with and without fertilizer (Greer et al., 1992b). Results from these simulations were expressed as % Yield loss from uneroded. Presenting the results in this manner reduces the potential problems with predicting a particular farmers yield. As well, giving the percent yield from optimum (uneroded) effectively makes these loss curves independent of cropping managements.

Currently, Prairie Farm Rehabilitation Administration (PFRA) Area Conservationists are using these curve to calculate the cumulative and annual cost of soil erosion.

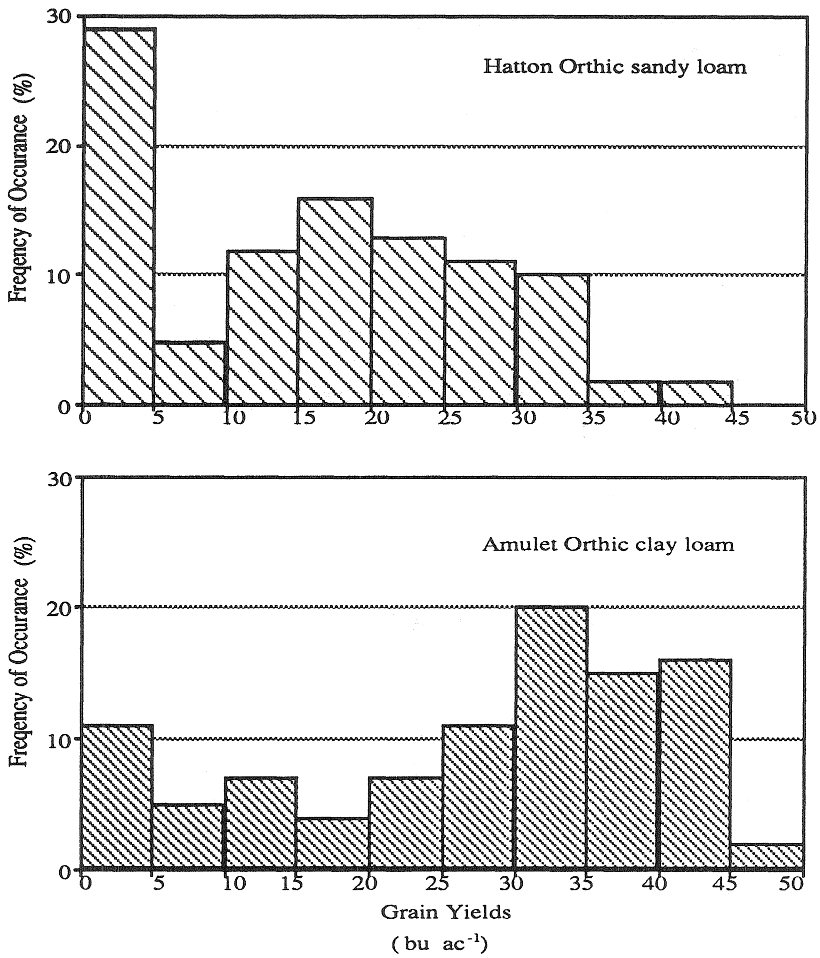
SimPLE Decision Support:

Risk Assessment of Zero-till Continuous Cropping.

SimPLE can be used to simulate grain production under a continuously cropped wheat rotations, given any combination of soil, fertilizer, erosion, and climate. The following is an example of how this flexible system was used to assess the benefits and risks of implementing a soil conserving Zero-till management on my own farm in the Dry Dark Brown soil zone.

Soil associations were individually simulated and the mean yields and risk of crop failure (≤ 5 bu ac^{-1}) were weighted to represent the entire farm. Comparisons could then be made against the historic Wheat-Fallow (50/50) management where mean weighted yield was 11 bu • cultivated ac^{-1} and the risk of crop failure was 10%.

Figure 4. ***SimPLE*** predicted frequency of obtaining each range of grain yield on two soil types .



Common sense interpretation of the probability distributions suggest that the heavier the textured Amulet (AMA) soils were more suited to zero-till management than were the lighter the textured Hatton (HTA) soils (Figure 4).

Compared to the historical 50/50 management, zero-tilled continuous wheat with fertilizer has more frequent crop failures (22%), although the mean weighted yield is greater (~20 bu • cultivated ac^{-1}). Further economic analysis depends on price assumptions for fertilizer, wheat, machinery upgrade and on the producers attitude toward increased risk. Nevertheless, knowledge of the **amount** of yield gained and risk carried, is key to assessing if the extra 9 bu ac^{-1} pays for the increased cost and risk of a zero-till system.

FUTURE USES FOR *SimPLE*

Simulating yields based on weather, soil type, fertilizer management and erosion allows one to compare any combination of these factors. For example, grain yield response to changing climate can suggest where future production may or may not be feasible. Also, tracking soil organic matter C and total C respiration from soil and residue may be useful in assessing which soil, fertilizer and weather regime lead to more or less CO_2 evolution.

SimPLE can aid in assessing soil aggrading or degrading managements. Given some level of erosion, a specific soil-climate-management combination will sustain productivity when residue addition, *SOMC* formation and soil loss equilibrate. Calculating this tolerable soil loss (T value) is possible using successive ***SimPLE*** runs.

CONCLUSION AND FUTURE RECOMMENDATIONS

Building a simulator of productivity lost by erosion using knowledge which described how a soil supplies water, N and P, how erosion changes the supply, and how much grain is produced from these nutrients was successful. Significantly more variability in observed yields was explained by the model than by the strongest factor (precipitation) alone. In studies where erosion was severe, 74% of the variability in observed yields was explained by ***SimPLE*** predictions.

SimPLE is a useful aid in assessing the long-run cost of soil erosion on grain yield. Current versions of this program have also been used, albeit very crudely, as a true Decision Support system.

Future work should concentrate on improving options for interpreting ***SimPLE*** output and increasing the flexibility in cropping scenarios. Enhancing the logic in ***SimPLE*** should be done with care. Each piece of logic should be added only if it is stronger and more probability than all other known pieces of logic. This stepwise addition should be inspired by failed reality tests, and not by the fact that the process is simply known to occur. Added logic must improve the predictive capacity overall, or in the selected circumstance within which more accuracy was desired.

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Appendix A: Model Input Parameters

Variable Name	Units	Description and Value Range
GS ppt	cm	rainfall from May to July (8 to 35 cm)
SWE ppt	cm	precipitation from August to April (8 to 35 cm)
mean GS temp	°C	mean temperature May to July (8 to 20 °C)
SOMC	kg C /ha to depth of solum	≥ 0
SOLUM	cm	≥ 0
clay	% by weight	≥ 0
silt	% by weight	≥ 0
Cond Ck	mS/cm in subsoil	≥ 0 ≤ 20
Infil	unitless	≥ 1 ≤ 6
agg	unitless	≥ 1 ≤ 6
Nfert	kg N /ha	≥ 0
Pfert	kg P /ha	≥ 0
Erosion	Mg/ha/yr	≥ 0